A Study of Combustion Behavior of High-Pressure Pulse Sprays

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論文内容要約

Chapter 1 Introduction

Nitrogen oxides (NO_X) cause human health issues and environmental pollution. They are produced through combustion processes. The combustion process has been improved to prevent the production of NO_X. Pulse combustion, which produces an intermittent flame by an intermittent supply of fuel, is one of the combustion techniques and can reduce NO_X emissions. However, the pulse combustion technique is not applied to spray combustion. Thus, in the present study, the pulse combustion and pressure spray techniques were combined to decrease the production of NO_X in the spray combustion, and the combination was named as high-pressure pulse spray combustion. The atomization, vaporization and combustion characteristics of the high-pressure pulse spray combustion were investigated by using experimental and numerical approaches. First of all, the phenomena and modeling of spray and pulse combustion in previous studies were reviewed to provide the foundations in this thesis (chapter 2). Subsequently, chapter 3 demonstrated the effects of injection pressure on the atomization and combustion characteristics experimentally. Chapter 4 focused on the vaporing sprays and discussed the effect of multiple injections on the atomization and vaporization characteristics. In chapter 5, the NO_X reduction mechanism in the laminar pulse combustion was considered. In addition, Chapter 6 pointed out the NO_X reduction mechanism in the high-pressure pulse spray combustion.

Chapter 2 Background: Literature survey and combustion physics

High-pressure pulse spray combustion is a combustion technique based on a combination of the pressure spray combustion and pulse combustion. In this chapter, phenomena, characteristics, theories, and models related to the pressure spray combustion and pulse combustion were explained. The pressure spray combustion is constructed from three phenomena: atomization, vaporization, and combustion. Each phenomenon was described separately. Spray A, which has been remarkably developed to characterize the vaporization and combustion of spray, was described. Models proposed to simulate those phenomena were introduced, especially flamelet approach. Finally, governing equations and discretized methods for Lagrangian and large eddy simulation frameworks were reviewed.

Chapter 3 Experimental investigations of atomization and combustion characteristics of high-pressure pulse spray

In Chapter 3, a common rail was applied to a stationary combustor, and the effect of fuel injection pressure (20–80 MPa) on the characteristics of atomization and combustion was investigated. The high-pressure pulse spray was formed with a common-rail system at atmospheric pressure and room temperature. In the atomization experiment, spray tip penetration, spray width, Sauter mean diameter were illustrated. In the combustion experiment, OH radical chemiluminescence emission intensity, combustion gas temperatures, and outlet gas concentrations were discussed. In the atomization experiments, an increase in the fuel injection pressure increased spray dispersion and decreased the Sauter mean diameter. This suggests that the combustion reaction is enhanced by the rapid mixing of fuel with air, due to the higher fuel injection pressure. In fact, the OH emission intensity and combustion gas temperature in the upstream region were higher than those in the downstream region of the combustor. The CO emissions in the high-pressure pulse spray combustion were much smaller than in a diesel engine, and the high-pressure pulse spray combustion tended to be complete combustion. Also, the NO_X emissions were reduced with an increase in the fuel injection pressure. Therefore, high-pressure pulse spray combustion can reduce NO_X emission and enhance the combustion load because of the increase in the fuel injection pressure.

Chapter 4 Numerical simulations of vaporizing pulse spray

In Chapter 4, large eddy simulations (LES) of pulse spray atomization and vaporization were performed to investigate the vaporization characteristics of multiple injections. With the same injection fuel mass in each spray timing, the effects of multiple injections on spray development, fuel vapor mass fraction field, evaporation rate, and local equivalence ratio were characterized. The Kelvin–Helmholtz–Taylor analogy breakup and Langmuir–Knudsen models were used for expressing the atomization and vaporization phenomena, respectively. Normal heptane was used as a surrogate for diesel, and it was injected 1–4 times at atmospheric pressure and a temperature of 1000 K. The results showed that, when the number of injections was small, the droplets tended to remain in the spray tail region owing to less evaporation. When the number of injections was large, the mass transfer of fuel vapor was restricted in the axial and radial directions. As for the atomization characteristics, the difference between the spray tip penetrations of the primary and secondary sprays was small in each case. However, the spray width of the secondary spray was smaller than that of the primary spray. The Sauter mean diameter of the secondary spray was larger than that of the primary spray, and the trend did not change with the number of injections. The evaporation rate was high in the case of a small number of injections, which meant that one spray consists of a large amount of fuel in the present study. By contrast, the total evaporation time of one spray was shorter in the case of a large number of injections. The histories of the evaporated masses of the secondary spray did not differ from those of the primary spray. Hence, multiple injections did not have a significant impact on the evaporation rate in this study. With regard to the local equivalence ratio, when the same amount of fuel was injected in the computational domain, the proportion of the high equivalence ratio region increased with the number of injections. Therefore, this indicates that the primary spray does not have a significant effect on the atomization characteristics of the secondary injected spray. Moreover, the primary spray does not have a significant impact on the subsequent evaporation behavior.

Chapter 5 Numerical simulations of pulse combustion of gaseous fuel

In Chapter 5, flames which inject methane intermittently were simulated to clarify the NO reduction mechanism of laminar pulse combustion. This study focused on laminar combustion fields because the turbulence makes the combustion phenomenon difficult. In addition, a detailed chemical model can be used for expressing the combustion phenomenon in the laminar combustion field, and then the NO production mechanism can be deeply investigated. The detailed chemical reaction mechanism was GRI-Mech 3.0. The effects of the injection cycle and injection velocity on the NO_X production were mainly investigated. In addition, the effects of injection cycle and injection velocity on temperature field, the amount of fuel burned in a premixed flame region, field of NO mass fraction, and the amount of the produced NO were discussed. In the results, the flame lift-off took place in the case of long injection interval and high injection velocity, and then a quasi-steady phenomenon whose period was longer than the injection cycle occured. Moreover, the proportion of premixed combustion region increased owing to the flame lift-off in the case of pulse combustion. As with the previous experimental study, the production of NO decreased with increases in injection velocity and injection interval. The reason of this can be that the flame becomes low NO emission flame owing to the increase of the proportion of premixed flame region, and consuming NO by the reburning mechanism is enhanced.

Chapter 6 Numerical simulations of high-pressure pulse spray combustion

In Chapter 6, the combustion of the sprays with multiple injections was simulated to uncover the NO reduction mechanism of the high-pressure pulse spray combustion. The number of injections was 1, 2, and 5 during 5 ms. In the case of two injections, the sprays at the low injection velocity were also simulated. Because of simulation time, beginning part of high-pressure pulse spray combustion was analyzed. Kelvin–Helmholtz-Modified Taylor analogy breakup, Langmuir–Knudsen, and flamelet generated manifolds (FGM) models were used to express the atomization, vaporization, and combustion phenomena, respectively. Volume frequency of mixture fraction, coherence between temperature and NO production rate, and emission index of NO (EINO) were discussed. The source code was validated by the comparison between the simulation results and the experimental results in 2 cases. From those results of the spray combustion simulations, the effects of the injection interval and injection velocity on the NO reduction mechanism were investigated. Since the FGM model was used as the combustion model, the database of FGM model was shown. Therefore, the NO reduction occurs in the case of the reaction advancing around stoichiometric mixture fraction. The trend of the fields of temperature, axial velocity, density, mixture fraction, C_2H_2 mass fraction, and NO mass fraction were illustrated, and they were consistent with the previous study. The volume fraction of mixture fraction showed the mixture fraction rapidly decreases owing to the turbulence. The premixed and diffusion combustion regions were identified with flame index, and the coherence between the temperature and NO production rate in each combustion region were demonstrated. Therefore, the NO should be reduced in the diffusion combustion region. The NO production cannot be described by only the temperature in the comparison between the histories of the high-temperature gas volume and EINO. From the comparison of integral of EINO during the 5 ms in each case, it is found that the NO consumption in the following part of the combustion is important for the decrease of the NO emissions, and the NO consumption is enhanced by the turbulent mixing of the residual products and the fuel. These should be the NO_X reduction mechanism of high-pressure pulse spray combustion.

Chapter 7 Conclusions

Chapter 7 provided the conclusions in each chapter. In this thesis, the phenomena, characteristics, and models in terms of atomization, vaporization, and combustion in the pressure spray combustion and pulse combustion were summarized for experimental and numerical investigations of high-pressure pulse spray combustion. The effects of injection pressure on the atomization and combustion characteristics of high-pressure pulse spray were experimentally clarified. The amount of NO_X decreased with an increase in injection pressure. The proportion of the high equivalence ratio region increased with the number of injections in vaporizing pulse spray. Novel NO reduction mechanisms of laminar pulse combustion and high-pressure pulse spray combustion were proposed. As abovementioned, the present study clarified the combustion phenomenon of the high-pressure pulse spray combustion to contribute reducing the NO_X emissions in the spray combustion.